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Low-Speed-Flight Research Program

STRUCTURAL CONSIDERATIONS OF PERFORATED MATERIALS USED IN BOUNDARY LAYER CONTROL

By

CHARLES B. CLIETT

Conducted Under

CONTRACT Nonr 223(00)

By

THE ENGINEERING RESEARCH STATION

of

Mississippi State College

Research Report No. 2

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F_{tuw}	Ultimate tensile stress for plywood having the face grain direction parallel to (with) the applied stress.
F_{tux}	Ultimate tensile stress for plywood having the face grain direction perpendicular to (across) the applied stress.
$F_{tu\theta}$	Ultimate tensile stress for plywood having the face grain direction at an angle θ to the applied stress.
F_{swx}	Ultimate shear stress for plywood elements for the case where the face grain is at zero and ninety degrees to the shear stress.

STRUCTURAL CONSIDERATIONS OF PERFORATED MATERIALS USED IN BOUNDARY LAYER CONTROL

BY: Charles B. Cliett*
Mississippi State College

INTRODUCTION

The problem of stabilizing a laminar flow over a surface has been the subject of a large amount of theoretical research. Long before the first flight by man, this subject was receiving the attention of some of the best research scientists. The first recorded recognition of the inherent instability of flow over a surface where discontinuities exist in the velocity was published in 1843.[1] As early as 1904, Prandtl[2] recognized the possibility of stabilizing the boundary layer by suction. Since that date considerable aerodynamic research has been conducted along these lines, but little progress toward actual application has been made. The structural side of boundary layer suction has caused considerable concern, but has been the subject of very little research. This paper is an effort to fill a small portion of the gap between the progress made on the aerodynamic considerations and the lack of progress made, due to little effort, on the structural considerations. A second purpose, and the more important one, is to stimulate the interest of structures-minded people and therefore lead to serious study of the subject

Aerodynamic Considerations

Among the many benefits which published research indicates may eventually be derived from control of the laminar boundary layer by suction are decreased drag, increased lift, an increase in maximum lift-drag ratio, a

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*This work was carried out as part of an Office of Naval Research contract conducted by the Engineering Research Station of Mississippi State College.

means of lateral control, a favorable influence on the shock boundary layer reaction, and increased efficiency for diffusers and bends.[3] Possible performance improvements such as a far slower stalling speed, increased maximum speed, greater range, shorter ground runs for both take off and landing, and better maneuverability, make further research in this field imperative. Safety considerations alone would provide sufficient incentive.

It is easily seen that the utility of an airplane would be greatly enhanced if boundary layer stabilization could be developed to permit a wide speed range. If the maximum speed of an airplane were five or six times the stalling speed, one could have a personal airplane flying at 180 miles per hour and landing at 30 miles per hour. Present day personal airplanes have, at most, a maximum speed only three times as large as the stalling speed.

The first method advanced for controlling the boundary layer by suction was by the use of single or multiple slots. Many papers have been published dealing with this process of control. Among the more important is one by Pfenninger.[4] He reported the use of a series of spanwise slots spaced along the chord from the leading to the trailing edge. Each slot was connected to an individual chamber through which the air was sucked. The individual arrangement made possible some saving in suction power since the suction flow required of such an arrangement varies with the position along the chord. Including the power lost by suction, he found drag reductions of from 33 to 50 percent. The range of low drag coefficient more than doubled, and the glide ratio was 1/200.

These are the results of tests made at a relatively low Reynolds number. Tests at a higher Reynolds number failed to show such favorable results. This Pfenninger attributed to an increase of tunnel turbulence caused by higher velocities.

Airfoils especially designed for boundary layer control by suction through slots have been advocated by Griffith. These were discussed extensively by Goldstein[5] in his Wright Brothers Lecture. The basic idea involved is that of producing a favorable pressure gradient over the entire region from the leading to the trailing edge. Many difficulties have been encountered during experimental procedures, but this method may well prove significant in the future.

In considering the design of a boundary layer control system it is important to maintain a laminar flow up to each slot, for if the flow becomes turbulent a great amount of suction is required to remove the turbulent boundary. For this reason there exists a critical spacing of slots which is less for the higher Reynolds numbers than for the low Reynolds numbers.

A boundary layer stabilization method which offers near infinitely close spacing of suction sources is the porous area suction method. In addition to fulfilling the demands for high Reynolds number stabilization, this method also reduces the destabilizing influences of surface defects, of foreign particles adhering to the wing, and of surface waviness.

Porous area suction has been accomplished through such materials as porous metals,[6] calendered nylon cloth,[7] and perforated sheet materials.[8] From the aerodynamic standpoint a porous material has the advantage that it provides stabilization of the laminar boundary with the least sensitivity to disturbances. However, unless the porosity is made variable according to the local requirements along the chord, a large power expenditure for suction will be required. A possible solution is to divide the suction area into smaller areas, each of which has a separate suction pressure. This method nevertheless complicates the control of suction pressure as well as the internal wing structure.

Perforated surfaces, consisting of closely spaced holes running spanwise in rows spaced the critical distance apart, offer a possibility of controlling the porosity by the size of the holes and by their spacing chordwise and spanwise. In the research reported in reference 8 the laminar boundary layer was maintained to the trailing edge on the top surface of a classical airfoil with exceedingly small suction power.

It is because of these aerodynamic possibilities that this study on the structural aspects of perforated sheet was made.

<u>Structural Considerations of Various Methods of Suction Boundary Layer Control</u>

The use of multiple slots as the source of suction for boundary layer stabilization would present several structural difficulities. The problem of torsional stability would of necessity have to be accomplished by an entirely new process. Since the suction power required varies along the chord, individual compartments with separate flow velocities would be needed to keep the power requirement low so that an overall efficiency gain could come from the boundary layer stabilization. The interior of the wing would then become a series of individual compartments, critical in design due to the duct loss factor. Because of the many cutouts and sharp bends that would be required, the fatigue problem would also become critical. With these thoughts in mind, it would seem that any design capable of meeting the aerodynamic requirements should result in a strength-weight ratio so low that the use of this method of stabilization is hardly practical. It is the author's opinion that use of multiple slots is not feasible. Single slots, such as those used near the trailing edge, could be handled successfully.

Porous metals (like sintered bronze)[9] that have been recently developed, offer very little hope of becoming structural materials for aircraft. They

are not only heavy, but have very low strength properties. Sintered bronze cannot be machined if it is to be used for suction because the pores fill readily. Although the porosity can be changed by manufacturing procedures, it presently cannot be controlled within practical limits. For model purposes its strength is probably sufficient, but in actual application it would be merely excess weight added to the structural components of a wing.

Porous cloth and fabric require support at close intervals.[8] Unless carefully designed ribs are used, this internal support may decrease the strength-weight ratio and tend to offset the aerodynamic improvements.

Perforated sheet materials have this structural advantage over slots: torsion can be carried by the sheet. Since separate chamber pressures can be eliminated by varying the porosity, an additional advantage in structural simplification results. In fact, the technique of laminar boundary layer stabilization using a perforated surface may involve little additional structure over the conventional airplane wing design. It is for this reason that this research on the structural properties of perforated sheet materials was undertaken.

STRUCTURAL PROPERTIES - PERFORATED SHEET MATERIALS

In the appendix will be found a description of the design and preparation of the test specimens, the testing procedures, and a description of the testing machines used in the experimental program. Where possible, the procedures used conformed to the Standards of the American Society for Testing Materials.

Ultimate Tensile Strength - Perforated 24ST-3 Aluminum Alloy Sheet

For the case of uniform tension, the mathematical theory of elasticity indicates that a single hole placed in the center of a plate of isotropic material of infinite width produces a stress concentration at the edge of the hole of three times the value that would be produced if no hole was present. Various experimental methods, such as photoelasticity and the brittle material method have shown that such a concentration does exist and that the magnitude is of the order previously stated.[10]

The chief interest herein is, of course, beyond the point where actual yielding of the material occurs. For years it has been assumed, and rightly so, that the stress concentration does not control the ultimate failure of such ductile materials as structural steel. Holleman[11] has verified this by tests on annealed X4130 steel. His experiments show that no reduction of strength occurs when the tensile stress produced is calculated on the basis of net area. In other words, regardless of the size of the hole or of the number of holes placed in a single transverse row, there is no reduction in the ultimate net area stress. Consideration of the conventional stress-strain diagram for this material leads one to realize that these results were to be expected. Beyond the yield point, this material yields, for all practical purposes, without any increase in stress. Therefore, even though yielding at the hole edge occurs very early in test, no stress concentration remains when ultimate failure occurs.

Study of the stress-strain diagram for the less ductile 24ST-3 aluminum alloy reveals that different conclusions must be drawn for materials of its type. Certainly the point at which it yields is not well defined; and of more importance, the stress required beyond yield, for any definite strain, increases until ultimate failure occurs. This means that some stress concentration exists even at the instant of ultimate failure, and that this material's efficiency (based on net area) will be less than 100 percent. Results by Holleman,[11] Stevenson,[12] and by this author (see Figure 1) verify the conclusions drawn for the case of a single hole placed in the center of the test specimen.

As can be seen in Figure 1, the percent of original strength based on net area decreases rapidly with an increase in hole size until approximately 18 percent of the cross section area has been removed. Here a steady increase in the percent of original strength based on net area becomes apparent as the area removed increases. If one keeps the actual stress-strain diagram in mind, a probable explanation of this phenomenon may be had from the theory of elasticity. The equation for the normal unit stress on a cross section, which includes a single hole in the center, in terms of the unit stress on a cross section sufficiently removed so that no effect of the hole is present, is:

$$S_t = \frac{S_o}{2}\left(2 + \frac{r^2}{x^2} + 3\,\frac{r^4}{x^4}\right) \qquad 10$$

Where: r is the radius of the hole,

x is the distance to any point on the cross section measured from the center of the hole and

S_o is the unit stress on a cross section unaffected by the hole. It can thus be seen that the section near the hole yields long before other portions reach the yielding stage. Of course, once yielding has occured,

the equation is no longer valid, since the assumption of elastic behavior does not hold. It is probable, however, that the portion below yield stress is stressed by a similar equation.. We know that for the aluminum alloy continued yielding does not occur without additional stress. Thus the procedure continues to failure with a stress concentration that becomes more intense as the point in question is moved from the edge of the sheet to the edge of the hole.

The portion of the curve (Figure 1) which shows a definite decrease in efficiency has in all likelihood a slow process of failure. The stress concentration is on a limited portion of the cross section, and actual failure probably occurs here when the rest of the cross section is still capable of carrying the entire load. Therefore, the rupture slowly proceeds out from the hole until the remaining portion can no longer carry the entire load. This theory was apparently verified during actual testing, since an actual slow process of yielding did occur over a period of time, decreasing in length as the portion of the cross section removed by the hole increased.

That the curve shows an increase in efficiency after more than 18 percent of the cross section has been removed is as was expected. The remaining portion of the cross section, as the area removed is increased, falls to an increasing degree within the highly stressed portion. Therefore, the strain is more nearly uniform at time of failure, which results in a higher efficiency based on net area.

Figure 1 shows no values for cases in which more than 50 percent of the cross section area was removed. By the theory presented above, the curve should slowly approach 100 percent and when only an infinitesimal portion of the cross section remains, should be at 100 percent. A limited number of tests were conducted beyond the 50 percent point, but wide scatter occured

and they were therefore considered unreliable. These points are, of course, only of academic interest, since the removal of as much as 50 percent of a given cross section area is neither necessary nor desirable for boundary layer suction.

Results by Holleman[11] and Stevenson[12] indicate that whenever a second hole is placed in the specimen, a reduction in efficiency occurs, whether the hole is placed in the same transverse row or elsewhere. This was verified (see Table 1) with one very encouraging exception. Their reports were based on test results in which the size of the holes placed in the specimen were relatively large. They were considering, in general, holes for attachments by rivets and bolts. Figure 2 presents results from specimens that had four 0.018 of an inch diameter holes in a transverse row, spaced 0.100 of an inch apart. Rows were spaced 0.100 of an inch apart and were varied in number from one to five. As can be seen from this figure, the addition of entire rows had no effect on the net efficiency of the specimens. Figure 3 presents similar results for a case in which four 0.031 of an inch diameter holes were spaced 0.100 of an inch apart in transverse rows. We can therefore say conservatively that the addition of extra rows of holes can be made with no decrease in efficiency, provided the hole diameter is no greater than 0.031 of an inch and if the holes are spaced at least 0.100 of an inch apart. Successful flight tests, in which boundary layer control was effected by suction through holes 0.018 of an inch and less in diameter and spaced 0.100 of an inch apart, have been conducted at Mississippi State College.[8] For practical purposes, then, it would seem that knowledge of the fact that holes of 0.031 of an inch in diameter can be used without a decrease in efficiency is all that is needed. Even more desirable however, is an understanding of the phenomenon that controls the spacing and, therefore, the limitations upon it.

Unsuccessful attempts were made by the author to find a theoretical method of predicting ultimate failure in tension for perforated sheet, but a reliable emperical method based on the test results from specimens with only a single hole in the center of the test section was found.

Articles published by Childs and Kelly[13] concerning studies of the effect of abrupt changes of the cross section on the unit stress of rubber models proved very interesting. Although the stress-strain diagram for rubber deviates app[illegible]ably from a straight line, even at low stress, at least some idea of strain distribution emerges from their research. A single hole placed in the center of a rubber model results in a strain distribution that can be closely approximated by a straight line that is, of course, maximum at the hole and minimum at the edge of the sheet. If, on the same transverse axis, an additional hole is placed in the model, and if we assume that the strain distribution for a single hole can be expressed by a straight line relation, the strain distribution - by the principle of superposition - becomes constant over the portion of the cross section between the two holes and at failure carries a stress equal to the ultimate tensile stress of the material.

By means of photoelasticity, Coker[14] has studied the stress concentrations on tension specimens in the elastic range that results from symmetrical fillets formed by semicircles at the plate edge. Where these fillets remove 25 percent of the cross section, the stress concentration amounts to only 1.37 of the average stress, and the area over which the stress concentration exists is a relatively small portion of the total cross section. As the percentage of the area removed by the fillets decreases, both the area affected by the concentration and the degree of concentration become smaller. Hence, the conclusion may again be drawn that, for all practical purposes when the holes

are of the type desired for boundary layer control by suction, the stress is constant over the cross section between the holes. Although it may seem that the use of such reasoning would lead to slightly unconservative results, such is not the case, as will be shown later.

If the above theory can be applied, there remains to be considered only the portion of the cross section that lies between the last hole in a row and the edge of the sheet. This information can be secured directly from tests in which only one hole was placed in the center of the sheet.

A combination of the theory of constant strain between two holes in a single transverse row and the experimental results from the effect of a single hole has been used to predict the ultimate failure of ninety-four test specimens. A comparison between the predicted ultimate failure loads and the experimental failure loads is shown in Figure 4. Specimens containing holes of diameters of 0.031 of an inch and of 0.018 of an inch were used. The number of rows was also varied from one to five. In some cases the holes were placed directly behind each other in the transverse rows, and in others they were staggered in such a way that the offset was exactly half of the transverse spacing. Sheet thicknesses of 0.025 of an inch and 0.040 of an inch were used for all cases. In Tables 3, 4, 5, and 6 of the appendix a description of each specimen will be found.

As is illustrated, variations between the predicted and experimental loads are relatively small. A variation of as much as five percent was the exception, and in only a few cases did one occur.

In all instances the ultimate failure loads were predicted on the basis of the mean ultimate tensile strengths of the aluminum alloy sheet concerned. Practical application of the preceeding theories would dictate the use of the

minimum guaranteed ultimate tensile strengths rather than the mean ultimate tensile strength.

Ultimate Shear Strength - Perforated 24ST-3 Aluminum Alloy Sheet

Table 7 and Figure 5 present the results of single-hole shear studies on 0.032 of an inch 24ST-3 aluminum alloy sheet. In these studies the effect of a single hole drilled in the center of the test area was determined. The hole diameters were changed so that the percent of the failure cross section area removed varied from zero to above fifty percent. Throughout this range the remaining material proved capable of carrying the ultimate shear load of the unperforated material. Each of the seventy-two specimens developed an average ultimate shear stress above the minimum guaranteed ultimate shear stress of the unperforated material (ANC-5, June 1951.)[15]

Assuming all remaining material capable of developing the full ultimate shear strength of the unperforated material, the ultimate failure loads of the thirty-six perforated specimens listed in Table 8 were predicted. A comparison of these predicted failure loads and the corresponding experimental failure loads is shown in Table 8 and Figure 6. The close agreement between these show that this method of predicting the ultimate shear failure is reliable for this perforated material.

Proof that additional holes other than those in the failure cross section can be added without a reduction in the efficiency of the material is also given in Table 8. As long as the holes are no larger than 0.031 of an inch in diameter and spaced no closer than 0.10 of an inch, there will be no reduction in the shear carrying ability of the specimen.

The predicted values shown are probable failure loads as they were predicted on the basis of mean shear strength of ten unperforated samples.

Practical application of this theory would call for use of the minimum guaranteed property as given in the ANC-5.[15]

Analysis Procedures - Plywoods

The method of least squares for observations of equal weight was applied to all experimental data received from tests involving plywood materials, but only the arithmetical mean and the probable error of a single observation were determined.[16] All data from plywood tests that are later presented in this report or in its appendix will thus be given in the form of $M \pm r$:

M is the arithmetical mean and

r is the probable error of a single observation.

Whenever the data were involved in computing such percentages as percent of original strength based on net area, only the arithmetical mean was considered.

Stress Concentrations - Woods and Plywoods

The intensity of the stress concentrations produced by a hole placed in the center of a sheet of wood that is under tension is dependent upon many variables. Large variations in Young's modulus, the shear modulus, and Poisson's ratio result in large differences in the value of the concentration factors produced in any given wood material as the direction of the applied tensile load is varied in relation to the grain direction. Since the relationships that exist between the moduli and Poisson's ratio vary from specie to specie (see Table 2-9 ANC-18),[17] a pattern determined for any given wood would very likely be quite different from what would exist in another specie under similar conditions. Just as the intensity of the concentration at the hole varies so does its effect on the material at any given distance from the hole.

Since the grain of the individual plies of plywood varies as to direction (generally aircraft plywoods have the grain of adjacent plies at right angles to each other), a more uniform strength and elastic property condition exists. As the tensile load is applied at different angles to the face grain direction, however, a considerable variation in the stress concentration factor still occurs. (The application of equations 2.14 and 2.15 of the ANC-18[17] of June, 1951, to any plywood material will readily verify this statement.) Also, differences in the stress concentration pattern around a hole will be found for similar plywoods constructed from different species of wood. For these reasons the results to be presented later must be considered to apply only to the plywoods in question and to these plywoods under the specified conditions. The performance of other plywoods under similar conditions surely can be expected to be similar in nature and general conclusions can be drawn concerning them, but direct use of the data contained herein is not possible.

Ultimate Tensile Strength - Perforated Plywoods - Face Grain Direction Parallel to the Loading Direction

The results of single hole studies on 1/8 inch mahogany-yellow poplar plywood are shown in Figure 7. A single hole was drilled in the center of the test specimen, and its effect upon the ultimate tensile strength of the specimen was determined. The loading in every case was parallel to the face grain direction.

It is obvious from this plot that the stress concentration produced by the hole controls to a large degree the ability of the material to resist the ultimate tensile load. The conventional stress-strain diagrams for the two woods involved are a key to this action. The steepness of their stress-strain curves even after the proportional limit has been exceeded means that a large stress concentration must still exist at the time of ultimate failure.

That is, even though the large stress concentration factor produces local yielding at the hole early in the test, this yielding does not continue without a continued increase in the local stress. Therefore at the time of first local failure and instantly thereafter when total failure occurs, an uneven stress distribution exists, and thus a reduction in efficiency based on net area occurs.

As the percentage of the area removed by a single hole increases from zero, a very rapid reduction in efficiency based on net area occurs. This rapid reduction continues until about twenty-five percent of the cross section area has been removed and then the effectiveness of the remaining material is about sixty percent. When from twenty-five to above fifty percent of the cross section area has been removed, the efficiency of the remaining material for all practical purposes is constant at sixty percent. No tests were conducted where more than fifty-five percent of the cross section was removed by a single hole.

A greater reduction in efficiency occurs in the plywood than in the aluminum alloy. Also, in the range from zero to twenty-five percent cross section area removed by a single hole, the rate of reduction is much higher for the plywood. This reduction in efficiency and its rate can at least be partially explained by two factors. First, the stress concentration factors produced in the core of the plywood material while it is still stressed in the elastic range is much larger than that produced in the aluminum alloy. If no relief is considered to be received from the face plies, this factor as calculated from equation 2.14 of the ANC-18[17] is 5.48 as compared with 3.0 for the aluminum alloy. The face material itself, considering no increase from the core, has factor of 2.35. In any event the overall concentration considerably exceeds that produced in the aluminum alloy. Second, the extreme steepness of the tensile stress-strain curve beyond the elastic limit continues much of this concentration until ultimate failure occurs.

That the curve fails to continue its downward trend beyond the point where twenty-five percent of the cross section area was removed was to be expected. As the area removed increases, the remaining portion falls to an increasing degree within the high stressed portion, and therefore is more nearly equally stressed at the time of failure. If the tests had been continued beyond fifty-five percent cross section area removed, very likely an increasing efficiency based on net area would have been found. Possibly no earlier increase was found due to the fact that the material some distance from the hole was little affected by the stress concentration produced by the hole.

If at the time of ultimate failure the theory of constant strain between two properly spaced holes holds for perforated plywoods, only the results of Figure 7 are necessary for predicting the ultimate failure load in tension for this material. On the assumption that all material between two adjacent holes is capable of carrying the ultimate tensile stress of the unperforated material and that the portion between the last hole in the row and the edge of the sheet is capable of carrying only that percentage found in the single hole studies (see Figure 7), the ultimate failure loads have been predicted for all specimen types listed in Table 10. Figure 8 gives a comparison of the predicted and experimental failure loads for these specimens, and, as shown, good agreement exists. Table 10 and Figure 8 also show predicted and ultimate failure loads for perforated 0.070 mahogany-mahogany plywood. Good agreement also exists for this material.

Proof that these materials' load carrying abilities are not reduced by other holes placed the proper distance from the failure cross section is also given in Table 10. If the spacing is at least 0.10 of an inch for hole diameters in the range 0.018 to 0.031 of an inch, no reduction will occur.

Spacing in a single cross section row is not limited to this figure, but additional rows must be spaced this distance apart. The results of tests nine and eleven (Table 10) show that if the spacing of the rows is 0.05 of an inch, considerable reduction in efficiency does occur.

Predicted failures, for comparison purposes, were always made on the basis of the mean ultimate tensile stress of the unperforated material. For practical use of the preceeding theory, the ultimate failure loads would necessarily have to be predicted on the basis of the minimum guaranteed properties.

Ultimate Shear Strength - Perforated 1/8 Inch Mahogany - Yellow - Poplar Plywood - Loading Direction Parallel or Perpendicular to the Face Grain

The results of single hole shear studies on 1/8 inch mahogany-yellow poplar plywood are shown in Figure 9. The affect of various size holes drilled in the center of the test area on the specimens' ultimate shear strengths were determined. For these studies the face grain was always perpendicular to the direction of loading and therefore failure was always across the face grain.

As shown in Figure 9, the percent area removed by a single hole was varied from zero to fifty percent. For all practical purposes the load-carrying ability of the remaining material did not diminish or increase, regardless of the size of the hole drilled in the test area. In all instances the experimental average net area stress exceeded the guaranteed minimum strength as published in the ANC-18[17] for this material.

With the preceeding results on this material and the results from the aluminum shear tests as a guide, it was assumed that the ultimate shear strength of this material when perforated could be predicted by considering

the remaining material fully capable of carrying the ultimate shear stress of the unperforated material. A comparison of predicted and experimental ultimate failure loads for six variations of perforated 1/8 inch mahogany-yellow poplar plywood with the face grain perpendicular to the loading direction is shown in the first half of Table 12. Close agreement between theory and experiment is shown; and as a result of this, the ultimate failure loads for similar specimens whose face grain was parallel to the loading direction were predicted. The second half of Table 12 gives a comparison of these predicted values with the experimental failure loads, and shows that the method of predicting failure is reliable in this case as well as when the loading was perpendicular to the face grain.

That the addition of extra rows of holes spaced at a minimum distance apart of 0.10 of an inch had no effect on the load-carrying ability of the specimens is also shown in Table 12. At a minimum it can be stated that as long as the holes for perforations are no larger than 0.031 of an inch in diameter and the rows are spaced at least 0.10 of an inch apart, no reduction in load-carrying ability will result from additional holes not in the failure cross section.

All predicted failure loads previously mentioned were computed from the mean of tests on the unperforated material. Practical application of this theory of failure would have to be on the basis of the minimum guaranteed properties for this unperforated material.

<u>Ultimate Tensile Strength Perforated Plywood - Load Applied at 45 Degrees to the Face Grain Direction</u>

Section 2.611 of the ANC-18[17] of June 1951 gives the following equation for the determination of the ultimate tensile strength of narrow plywood

elements having their face grain at any angle (θ) to the loading direction.

$$F_{tu\theta} = \sqrt{\left(\frac{\cos^2\theta}{F_{tuw}}\right)^2 + \left(\frac{\sin^2\theta}{F_{tux}}\right)^2 + \left(\frac{\sin\theta\cos\theta}{F_{swx}}\right)^2}$$

The minimum guaranteed properties of 1/8 inch mahogany-yellow poplar plywood are

$$F_{tuw} = 6220 \text{ p.s.i.}$$

$$F_{tux} = 4030 \text{ p.s.i.}$$

$$F_{swx} = 1440 \text{ p.s.i.}$$

If these minimum properties are applied to the preceeding equation, it is found that the minimum failure stress to be expected from tensile tests with the face grain at forty-five degrees to the direction of loading is 2650 p.s.i. For a one inch wide test specimen, this would mean a minimum ultimate failure load of 331 pounds. The experimental failure load based on ten test specimens was found to be 362 $\pm$ 17 pounds, and the least failure load was 340 pounds. These ultimate loads are thus in good agreement with the predicted values of the ANC-18.[17] Failure in every case was at forty-five degrees to the loading direction, that is, parallel to the face grain.

Previously it has been shown that full ultimate tensile and shear strengths are developed in the material remaining between any two holes in a perforated plywood. (This statement is restricted to the cases in which the hole diameters are in the range of 0.018 to 0.031 of an inch and the spacing is no greater than 0.10 of an inch.) If this theory is applied to perforated 1/8 inch mahogany-yellow poplar plywood loaded in tension at forty-five degrees to the face grain direction, the minimum failure stress to be expected becomes

$$F_{tu45} = 2650 \text{ p.s.i.}$$

Since failure occurs along a line at forty-five degrees to the loading direction, the minimum average stress over the failure area should be 2650 p.s.i. divided by 1.414 or 1875 p.s.i. If the fact that the material between the last hole in a row and the edge of the sheet does not develop full strength under tension is considered (see Figure 5), the minimum failure load can be predicted using this average minimum stress.

As an illustration, consider the case in which a 0.018 of an inch diameter drill is used to perforate the 1/8 inch mahogany-yellow poplar plywood. If the holes are spaced in such a way that the transverse spacing is 0.10 of an inch, the longitudinal spacing is 0.05 of an inch, and the transverse rows are staggered in relation to each other; the predicted minimum failure is 243 pounds. Actual experiment gave a failure load of 275 ± 14 pounds based on ten specimens, with a minimum failure load of 245 pounds. If failure is predicted on the basis of the mean of the experimental results for the unperforated material rather than on the ANC-18[17] minimum properties, the probable failure load is found to be 264 pounds which compares favorably with actual results.

For the case in which the 0.018 of an inch diameter holes were spaced 0.05 of an inch apart in transverse rows and the rows were spaced 0.10 of an inch apart and placed directly behind the preceeding row, the following are the results. Experimental ultimate failure is based on ten test specimens.

Predicted minimum failure-------284 pounds

Minimum experimental failure---291 pounds

Probable failure---------------309 pounds

Experimental failure-----------309 ± 10 pounds

For 0.070 mahogany-mahogany unperforated plywood loaded in tension at forty-five degrees to the direction of the face grain, the ANC-18[17] equation predicts a minimum failure stress of 3800 p.s.i. This results in a guaranteed minimum of 2690 p.s.i. average stress over the failure area. For a one inch wide test specimen the minimum ultimate load to be expected is then 266 pounds. Experimental results from ten test specimens gave a value of 275 $\pm$ 10 pounds.

A comparison of the predicted ultimate failure and experimental ultimate failure loads for perforated 0.070 of an inch mahogany-mahogany plywood, with the face grain direction at forty-five degrees to the loading direction, follows. For the case in which 0.018 of an inch diameter holes were drilled 0.10 of an inch apart in transverse rows, and the rows were staggered in relation to each other and spaced 0.05 of an inch apart, the loads were

Predicted minimum failure———194 pounds

Minimum experimental failure——198 pounds

Probable failure———————201 pounds

Experimental failure—————210 $\pm$ 12 pounds.

For the case in which the 0.018 of an inch diameter holes were spaced 0.05 of an inch apart in transverse rows and the rows were spaced 0.10 of an inch apart and directly behind the preceeding row, the comparison was as follows

Predicted minimum load————219 pounds

Minimum experimental failure——215 pounds

Probable ultimate failure———226 pounds

Experimental ultimate failure—220 $\pm$ 8 pounds

The preceeding cases seem to substantiate the theories presented previously and to make possible the use of the following procedure for predicting ultimate failure of perforated plywood elements that are loaded in tension at forty-five degrees to the face grain direction.

(1) Consider the material that exists between any two holes capable of carrying the ultimate tensile stress of the unperforated material.

(2) Consider the efficiency of the material between the last hole in a row and the edge of the sheet to be reduced as shown in Figure 7.

(3) To assure that the prediction is the minimum failure load possible, use minimum guaranteed tensile and shear properties.

<u>Strength of Plywood Perforated by Producing with a Needle</u>

An investigation was made to determine whether plywood perforated by punching with a needle would be stronger than similar plywood perforated by drills. It was thought that perhaps the needle would merely separate the fibers of the wood instead of rupturing all in its path as drilled holes would do. If merely this separation occured a considerable increase in strength might result.

Experimental evidence seemed to verify this when tests were conducted on tension specimens. This was particularly true when the loading was parallel to the face grain. Very little increase in efficiency was noted when tension specimens were loaded perpendicular to the grain, and from no gain to possibly a small loss when loaded at forty-five degrees to the face grain direction. In all instances a reduction in efficiency as compared to the efficiency of drilled specimens occured when the perforated plywood was tested in shear. This reduction was as great as ten percent in some instances.

The holes produced by punching were elongated considerably over those drilled. This would indicate the possibility of much larger stress concentrations and thus less efficiency. Since less open cross section area results, the efficiency of the holes, as far as boundary layer control is concerned, would be much less than the efficiency of drilled holes.

CONCLUSIONS

1. From a consideration of both the aerodynamic and structural aspects, indications are that any early application of boundary layer control by suction can most advantageously be applied through use of perforated lifting surfaces of conventional design. All other methods previously advocated result in less efficiency from either the aerodynamic or structural view point or from both.
2. The theories presented in this report for predicting the ultimate tensile and shear strengths of perforated 24ST-3 aluminum alloy sheet can be used for design purposes. Although the accuracy compares well with the accuracy of other stress analysis procedures, the use of a factor of 0.95 of the predicted value would guarantee conservative analysis. The decrease in the strength-weight ratio of the perforated aluminum alloy as compared with the unperforated alloy should by no means offset the aerodynamic imporvements received from boundary layer control by suction.
3. The theories presented for the prediction of the ultimate tensile and shear strengths of perforated plywood are suitable for design purposes. The percent reduction in strength-weight ratio is slightly higher for the plywoods than for the aluminum alloy due to the larger effect of the perforations on the ultimate tensile strength of the plywood. This can be explained by the types of stress-strain curves possessed by the materials concerned. Beyond the yield point, the slopes of the stress strain curves decrease very little, and therefore the degree of the stress concentration produced at the hole when the material is stressed below the yield point decreases very little as the material is stressed to ultimate tensile failure.

4. The fact that additional holes of the type needed for boundary layer control by suction can be added without a reduction of efficiency, as far as the tensile and shear strengths of the materials studied are concerned, is of primary importance. Without further investigation the addition must be limited to holes of no greater diameter than 0.031 of an inch and minimum spacing equal to 0.10 of an inch.
5. The theories previously discussed must be applied only to the aluminum alloy and the plywood materials studied. Generalities concerning the characteristics of other aluminum alloys and other plywoods can be drawn, but direct application of the data presented is not possible.
6. Perforated plywoods produced by drilling are more efficient structuraly than perforated plywoods produced by punching with a needle.
7. Further investigations, particularly of the panel buckling characteristics and of the fatigue strength of perforated materials, need to be made before final conclusions can be made in regard to the structural suitability of this procedure of boundary layer control by suction. Tests to determine the flexure fatigue strength of perforated 24ST-3 aluminum alloy sheet are presently being conducted, and the results will be reported at a later date.

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APPENDIX

Materials

The aluminum alloy used in these experiments was generously furnished by the Aluminum Company of America. Every care was taken by the company to insure that the aluminum alloy would arrive free of scratches. Bare 24ST-3 aluminum alloy was used throughout the program in order to have as homogenous a material as possible. The ultimate tensile strength, based on the average of six specimens of each type, was found to be 65,600 p.s.i. for the 0.040 of an inch thick sheet, 65,000 p.s.i. for the 0.032 of an inch thick sheet, and 64,500 p.s.i. for the 0.025 of an inch thick sheet. The ultimate shear strength for the 0.032 of an inch thick sheet was found to be 44,100 p.s.i. (this figure represents the average of ten test specimens).

Aircraft plywood of two types was used in the testing program. All 1/8 inch specimens were made from forty-five degree mahogany-yellow poplar plywood. All 0.070 of an inch specimens were cut from forty-five degree mahogany-mahogany plywood.

The following strength properties were determined from the mean strength of ten test specimens. For the 1/8 inch material the ultimate tensile strength where the face grain was parallel to the direction of loading proved to be 6700 p.s.i., and when the face grain was forty-five degrees to the direction of loading 2050 p.s.i. The ultimate shear strength for the case where the face grain was perpendicular to the loading direction was 1640 p.s.i. The ultimate tensile strength of 0.070 of an inch mahogany-mahogany plywood when the loading direction was parallel to the face grain direction was found to be 7200 p.s.i. The shear strength of this material was not determined.

Specimen Design

Plywood Tension Tests: The ultimate tensile strength of the plywood materials was determined by the methods described in the A.S.T.M. Designation D 805-47.[18] Specimen type B was used as dictated in these specifications. The ultimate tensile strength of unperforated plywood with the face grain direction at forty-five degrees to the direction of loading was determined from rectilinear specimens, one by four inches. All perforated strength properties were also determined from the one by four inch specimens.

Plywood Shear Tests: The shear strength of all plywood elements was determined by the "Alternate Method Using Tension Type Shear Specimen", as given in the A.S.T.M. Designation D 805-47.[18] No change was made in the basic specimen design for tests of the perforated materials.

Aluminum Tension Tests: Tension tests of the basic material and of the perforated material were made using the standard sheet metal specimen of the American Society for Testing Materials (Designation E 8-46.)[19] Every specimen rigidily conformed to these requirements or was rejected after it was machined. The requirements include the proper test section width, length, and taper ratio. In every case the direction of loading was parallel to the direction of rolling of the sheet.

Aluminum Shear Tests: No standards exist for determination of the shear strength of sheet metals using a tension type shear specimen. No standard shear tests by other methods are suitable for the determination of the shear strength properties of perforated materials. It was therefore necessary to design a specimen for these particular tests. The one selected was based on the principles involved in the standard tension type shear specimen for plywoods. If the exact dimensions of the plywood specimen are used, however;

the resulting failure will always be a tension failure rather than the desired shear type failure. The planform and dimensions of the test area of the specimen used is given in Figure 10. The direction of loading was always parallel to the direction of rolling of the sheet, and therefore all failures were parallel to the rolling direction.

Preparation of Specimens

The plywood tension specimens that conformed to the A.S.T.M. specifications were made by bolting a large number of rectangular pieces between two templates and then working to final dimension. The one by four inch rectangular sections were cut with a circular saw on an individual basis. No special finishing was given to the sides of the test specimen. Each specimen was carefully checked to be sure that it conformed to the proper test dimensions. The plywood shear specimens were also made on an individual basis, and all slots were cut by a jig saw.

The aluminum tension specimens were prepared on a group basis, entirely by machine. Forty or more one by nine inch blanks were mounted in a jig between two templates and machined to final dimensions on a milling machine.

All holes in the basic aluminum shear specimen were drilled individually by use of a jig. The slots were cut individually by use of a band saw.

In the preparation of the perforated materials, the spacing of the small holes was affected by gluing a section of graph paper to the basic specimen by use of rubber cement. The holes were then either drilled on a high speed drill press or punched by use of a needle. The punching method of preparation was used on only a portion of the plywood specimen. The large holes were drilled with a pilot drill and then reamed to proper diameter.

Moisture Content of Plywood Specimens

Since these studies were of a comparative nature and the absolute strength of a particular specimen under a certain moisture content was not desired, moisture contents were not determined. The method of testing was such that a large number of specimens could be tested in a short period and therefore all specimens whose relative strengths were to be compared were tested under the same climatic conditions.

Testing Machines

All tension tests on the aluminum alloy and the tension tests to determine the ultimate strength of the unperforated plywood were conducted on a Dillion Dynamomter. The loading range of this machine is 0 to 7500 pounds capacity. Calibration by use of a Morehouse Proving Ring was made, and an accuracy well within 20 pounds was found for the range of testing used in this program. The machine is loaded by use of a hand wheel with gearing of 40 to 1. Effort was made to make the loading rate as constant as possible, and no wide variation is believed to have occured.

All other plywood tension tests, all plywood shear tests, and all aluminum shear tests were conducted on the Riehle Plywood Testing Machine. This is a mechanical - lever testing machine of 1000 pound capacity whose rate of loading is 600 pounds per minute.

TABLE 1

The Effect of a Single Hole Placed in the Center of the Test Specimen on Its Ultimate Tensile Strength

24ST-3 Aluminum Alloy Sheet
Nominal Thickness 0.040 of an Inch

No.	Percent Area Removed	Average Stress Over Net Area	Percent of Original Strength Based On Net Area
0	0	65,600	100
1	3	63,300	97
2	4	62,400	95
3	4	62,700	96
4	6	62,000	94
5	6	60,000	91
6	6	60,000	91
7	8	63,000	96
8	8	59,900	90
9	8	58,000	88
10	8	58,800	90
11	12	58,000	88
12	12	57,300	87
13	18	56,200	86
14	18	58,800	91
15	20	59,600	91
16	25	57,200	87
17	25	56,300	86
18	25	57,600	88
19	31	63,000	96
20	31	61,600	94
21	34	63,500	97
22	34	61,600	94
23	36	65,000	98
24	37	62,500	95
25	37	61,700	94
26	39	63,000	96
27	39	63,000	96
28	40	61,200	93
29	40	65,400	99
30	45	62,000	94
31	45	62,500	95
32	50	64,000	98
33	50	62,200	95

TABLE 2

Effect of a Second Hole
Not in the Same Transverse Axis of First

24ST-3 Aluminum Alloy Sheet
0.032 Nominal Thickness

No.	Hole Diameter	Specimen Description	Net Area Stress in #/in^2	Reduction in Efficiency
34	.0595	Single hole in center	60,700	—
35	.0595	Second hole added, 0.12 in. above first in center of spec.	58,600	3.4
36	.0595	Same as (35)	58,600	3.4
37	.0595	Two holes centered on 45° diagonal, 0.20 of an inch apart	56,400	7.2
38	.0595	Same as (37)	55,700	8.2
39	.1200	Single hole in center	54,200	—
40	.1200	Single hole 0.24 of an inch above first in center of spec.	49,100	9.5
41	.1200	Same as (40)	49,700	9
42	.1200	Two holes centered on 45° diagonal, 0.20 of an inch apart	44,000	19
43	.1200	Same as (42)	43,200	20.3

TABLE 3

Tension Tests 24ST-3 Aluminum Alloy Sheet
Nominal Thickness - 0.025
Diameter of Holes - 0.031

No.	*Spec. Width	No. of Holes in Row	*Trans. Spac. of Holes	No. of Rows	*Row Spac.	**Row Loc. Rel. to Adj. Rows	Pred. Ult. Failure #	Exp. Ult. Failure #
44	.492	1	-	1	-	-	670	640
45	.492	1	-	1	-	-	670	630
46	.492	1	-	1	-	-	670	660
47	.492	2	0.100	1	-	-	638	600
48	.492	2	0.100	1	-	-	638	600
49	.492	2	0.100	1	-	-	638	610
50	.492	2	0.100	2	0.100	D	638	600
51	.492	2	0.100	2	0.100	D	638	600
52	.492	2	0.100	2	0.100	D	638	600
53	.492	2	0.100	2	0.100	S	638	625
54	.492	2	0.100	2	0.100	S	638	600
55	.492	2	0.100	2	0.100	S	638	600
56	.492	4	0.100	4	-	-	567	550
57	.492	4	0.100	4	0.100	D	567	560
58	.492	4	0.100	4	0.100	S	567	560
59	.492	4	0.100	4	0.100	D	567	570
60	.492	4	0.100	4	0.100	S	567	540
61	.492	4	0.100	4	0.100	D	567	570
62	.492	4	0.100	4	0.100	S	567	550
63	.492	4	0.100	4	0.100	D	567	580
64	.492	4	0.100	4	0.100	S	567	570
65	.492	5	0.100	5	-	-	526	500
66	.492	5	0.100	5	-	-	526	500
67	.492	5	0.100	5	-	-	526	510
68	.492	5	0.100	5	0.100	D	526	495
69	.492	5	0.100	5	0.100	D	526	500
70	.492	5	0.100	5	0.100	D	526	510

*All dimensions in inches.
**D - Rows directly behind each other.
S - Rows staggered relative to adjacent row, offset 0.05 of an inch.

TABLE 4

Tension Tests 24ST-3 Aluminum Alloy Sheet
Nominal Thickness - 0.040 Inches
Diameter of Holes - 0.031 Inches

No.	*Spec. Width	No. of Holes in Row	*Trans. Spac. of Holes	No. of Rows	*Row Spac.	**Row Loc. Rel. to Adj. Rows	Pred. Ult. Failure #	Exp. Ult. Failure #
71	.490	1	-	1	-	-	1120	1090
72	.490	1	-	1	-	-	1120	1100
73	.490	1	-	1	-	-	1120	1140
74	.492	2	0.100	1	-	-	1077	1060
75	.492	2	0.100	1	-	-	1077	1020
76	.492	2	0.100	1	-	-	1077	1050
77	.492	2	0.100	2	0.100	D	1077	1020
78	.492	2	0.100	2	0.100	D	1077	1030
79	.492	2	0.100	2	0.100	D	1077	1080
80	.492	2	0.100	2	0.100	S	1077	1050
81	.492	2	0.100	2	0.100	S	1077	1060
82	.492	2	0.100	2	0.100	S	1077	1070
83	.492	4	0.100	1	-	-	959	960
84	.492	4	0.100	2	0.100	D	959	960
85	.493	5	0.100	1	-	-	912	920
86	.493	5	0.100	1	-	-	912	940
87	.493	5	0.100	1	-	-	912	900
88	.493	5	0.100	2	0.100	D	912	870
89	.493	5	0.100	2	0.100	D	912	900
90	.493	5	0.100	2	0.100	D	912	890

*All dimensions in inches.
**D - Rows directly behind each other.
S - Rows staggered relative to adjacent row, offset 0.05 of an inch.

TABLE 5

Tension Tests 24ST-3 Aluminum Alloy Sheet
Nominal Thickness - 0.025
Diameter of Holes - 0.016

No.	*Spec. Width	No. of Holes in Row	*Trans. Spac. of Holes	No. of Rows	*Row Spac.	**Row Loc. Rel. to Adj. Rows	Pred. Ult. Failure #	Exp. Ult. Failure #
91	.490	1	-	1	-	-	720	730
92	.490	1	-	1	-	-	720	720
93	.490	1	-	1	-	-	720	700
94	.490	1	-	1	-	-	720	680
95	.490	2	0.100	1	-	-	672	670
96	.490	2	0.100	1	-	-	672	680
97	.490	2	0.100	1	-	-	672	690
98	.490	2	0.100	2	0.100	D	672	670
99	.490	2	0.100	2	0.100	D	672	670
100	.490	2	0.100	2	0.100	S	672	670
101	.490	2	0.100	2	0.100	S	672	670
102	.490	2	0.100	2	0.100	S	672	670
103	.490	4	0.100	1	-	-	632	650
104	.490	4	0.100	2	0.100	D	632	620
105	.490	4	0.100	2	0.100	S	632	600
106	.490	4	0.100	3	0.100	D	632	640
107	.490	4	0.100	3	0.100	S	632	620
108	.490	4	0.100	4	0.100	D	632	660
109	.490	4	0.100	4	0.100	S	632	600
110	.490	4	0.100	5	0.100	D	632	630
111	.490	4	0.100	5	0.100	S	632	620
112	.490	5	0.100	1	-	-	632	600
113	.490	5	0.100	1	-	-	632	620
114	.490	5	0.100	1	-	-	632	620
115	.490	5	0.100	2	0.100	D	632	600
116	.490	5	0.100	2	0.100	D	632	630
117	.490	5	0.100	2	0.100	D	632	630

*All dimensions in inches.
**D - Rows directly behind each other.
S - Rows staggered relative to adjacent row, offset 0.05 of an inch.

TABLE 6

Tension Tests 24ST-3 Aluminum Alloy Sheet
Nominal Thickness - 0.040 Inches
Diameter of Holes - 0.018 Inches

No.	*Spec. Width	No. of Holes in Row	*Trans. Spac. of Holes	No. of Rows	*Row Spac.	**Row Loc. Rel. to Adj. Rows	Pred. Ult. Failure #	Exp. Ult. Failure #
118	.500	1	-	1	-	-	1232	1200
119	.500	1	-	1	-	-	1232	1210
120	.500	2	0.100	1	-	-	1173	1140
121	.500	2	0.100	1	0.100	-	1173	1180
122	.500	2	0.100	2	0.100	D	1173	1180
123	.500	2	0.100	2	0.100	D	1173	1190
124	.500	2	0.100	2	0.100	S	1173	1150
125	.500	2	0.100	2	0.100	S	1173	1170
126	.500	4	0.100	1	-	-	1103	1140
127	.500	4	0.100	2	0.100	D	1103	1150
128	.500	4	0.100	2	0.100	S	1103	1140
129	.500	4	0.100	3	0.100	D	1103	1140
130	.500	4	0.100	3	0.100	S	1103	1170
131	.500	4	0.100	4	0.100	D	1103	1140
132	.500	4	0.100	4	0.100	S	1103	1170
133	.500	4	0.100	5	0.100	D	1103	1180
134	.500	5	0.100	1	-	-	1104	1070
135	.500	5	0.100	1	-	-	1104	1140
136	.500	5	0.100	2	0.100	D	1104	1120
137	.500	5	0.100	2	0.100	D	1104	1110

*All dimensions in inches.
**D - Rows directly behind each other.
S - Rows staggered relative to adjacent row, offset 0.05 of an inch.

TABLE 7

The Effect of a Single Hole Placed in the Center of the Test Area of a Test Specimen on Its Ultimate Shear Strength

24ST-3 Aluminum Alloy Sheet
Nominal Thickness 0.032 of an Inch

No.	% Area Removed	Average Stress Over Net Area in #/in^2	% Original Strength Based on Net Area*	No.	% Area Removed	Average Stress Over Net Area in #/in^2	% Original Strength Based on Net Area*
1	0	44,500	-	37	22	46,000	104
2	0	42,800	-	38	25	47,600	108
3	0	44,900	-	39	25	44,000	100
4	0	45,200	-	40	26	44,000	100
5	0	43,500	-	41	26	44,600	101
6	0	43,400	-	42	26	44,600	101
7	0	44,200	-	43	29.5	44,000	99
8	0	44,900	-	44	30.7	46,000	104
9	0	44,000	-	45	30.7	44,200	100
10	0	43,700	-	46	30.7	45,400	103
11	5.5	45,300	102.5	47	33	47,300	107
12	6.5	46,700	106	48	34	45,000	102
13	7.5	42,800	97	49	36.2	42,800	100
14	7.5	46,000	104	50	36.2	43,800	99
15	7.5	43,200	98	51	36.2	43,600	99
16	9	46,300	105	52	37.5	44,300	100.5
17	10.5	47,500	108	53	39.5	47,200	107
18	12	46,800	106	54	40.7	44,600	101
19	13.5	45,500	103	55	40.7	46,200	104
20	13.5	47,900	108	56	40.7	44,600	101
21	13.5	46,500	105	57	43	43,700	99
22	14	47,000	106.5	58	44	45,000	102
23	14.5	48,000	110	59	45.1	47,700	108
24	15	45,200	102	60	45.1	41,200	94
25	16	46,000	104	61	45.1	46,300	104
26	16.5	47,200	107	62	46	44,700	101
27	17	43,800	99	63	47	45,900	104
28	17.5	46,000	104	64	47.5	45,300	102.5
29	17.6	46,800	106	65	48.5	49,300	111
30	17.6	46,200	104	66	48.9	47,900	108
31	17.6	46,600	105	67	48.9	43,300	98
32	19.5	42,800	97	68	48.9	41,900	95
33	21.7	41,200	94	69	49.5	43,800	99
34	21.7	43,500	99	70	52.6	48,000	109
35	21.7	41,000	93	71	52.6	45,200	102
36	22	48,500	111	72	52.6	47,100	107

*Based on the average strength of specimens 1 through 10 which are the results of test to determine the ultimate shear strength of unperforated 24ST-3 aluminum alloy sheet. This average is 44,100 #/in^2 as compared with the minimum guaranteed value as given in the ANC-5 of 41,000 #/in^2.

TABLE 3

Ultimate Shear Strength - Perforated
24ST-3 Aluminum Alloy Sheet

Nominal Thickness 0.032 of an Inch

Spec. No.	Test Area* Length	Drill* Diam.	Trans.* Spac.	Long.* Spac.	No. of Rows	No. of Holes in Row	Exp. Ult. Failure in Pounds	Net Area Stress $\#/in^2$	Pred. Ult. Failure in Pounds
1	.3	.031	.1	.05	3	3	440	48,500	404
2	.3	.031	.1	.05	3	3	390	43,200	404
3	.3	.031	.1	.05	3	3	484	53,500	404
4	.3	.031	.05	.05	3	3	392	43,400	404
5	.3	.031	.05	.05	3	3	425	46,800	404
6	.3	.031	.05	.05	3	3	420	46,400	404
7	.3	.031	.1	.1	3	2	537	48,200	500
8	.3	.031	.1	.1	3	2	615	54,500	500
9	.3	.031	.1	.1	3	2	570	51,000	500
10	.3	.018	.1	.05	3	3	547	46,500	523
11	.3	.018	.1	.05	3	3	540	45,800	523
12	.3	.018	.1	.05	3	3	532	45,200	523
13	.3	.018	.05	.05	3	3	565	48,000	523
14	.3	.018	.05	.05	3	3	602	51,000	523
15	.3	.018	.05	.05	3	3	560	47,700	523
16	.3	.018	.1	.1	3	2	580	45.000	575
17	.3	.018	.1	.1	3	2	585	45,300	575
18	.3	.018	.1	.1	3	2	627	48,500	575
19	.3	.018	.05	.1	3	2	545	42,300	575
20	.3	.018	.05	.1	3	2	595	46,200	575
21	.3	.018	.05	.1	3	2	578	44,800	575
22	.5	.018	.05	.05	3	7	864	43,500	885
23	.5	.018	.05	.05	3	7	885	44,500	885
24	.5	.018	.1	.05	3	7	878	44,400	885
25	.5	.018	.1	.05	3	7	914	46,000	885
26	.5	.018	.1	.05	3	7	890	44,700	885
27	.5	.031	.1	.05	3	7	613	45,000	607
28	.5	.031	.1	.05	3	7	597	43,800	607
29	.5	.031	.1	.05	3	7	638	46,600	607
30	.5	.031	.1	.1	3	4	857	43,300	880
31	.5	.031	.1	.1	3	4	838	42,200	880
32	.5	.031	.1	.1	3	4	885	45,200	880
33	.4	.018	——	.1	1	3	812	44,800	805
34	.4	.018	——	.1	1	3	762	42,300	805
35	.4	.031	——	.1	1	3	740	46,800	700
36	.4	.031	——	.1	1	3	675	42,800	700

*All dimensions in inches.

TABLE 9

The Effect of a Single Hole Placed in the Center of a Test Specimen On Its Ultimate Tensile Strength

1/8 Inch Mahogany - Yellow Poplar Plywood
Grain Direction of Face Plies Parallel to Loading

Test No.	Percent Area Removed	Average Stress Over Net Area in p.s.i.	Percent Orig.* Strength Based on Net Area
1	2.5	5860 ± 189	88
2	5.5	4960 ± 250	74
3	7.5	5090 ± 380	76
4	10	5020 ± 653	75
5	12.5	4970 ± 550	74
6	15	4220 ± 574	63
7	20	4180 ± 440	62
8	25	3910 ± 270	58.5
9	30	3880 ± 352	58
10	36	4000 ± [illegible]24	60
11	40.5	4090 ± 443	61
12	45	3800 ± 458	58
13	50	4000 ± 384	60
14	55	3870 ± 300	58

*Based on mean of 10 specimens to determine the ultimate tensile strength of the unperforated material, mean stress 6700 p.s.i.

TABLE 10

Comparison of Experimental and Predicted Ultimate Failures
Perforated Plywood Tension Specimens

No.	Specimen Description	Predicted* Ultimate Failure in Pounds	Mean Ultimate Tensile Strength of 10 Specimens
1	1/8 inch mahogany-yellow poplar 0.018 inch diameter holes drilled with 0.1 inch transverse and longitudinal spacing-face grain parallel to loading. Complete cross section perforated	626	618 ± 32
2	Same as (1) with transverse rows staggered in relation to each other	626	631 ± 56
3	Same as (1) except holes punched with a 0.018 inch needle	626	652 ± 52
4	Same as (1) except 0.018 inch diameter holes drilled with 0.05 inch transverse and 0.10 inch longitudinal spacing	525	535 ± 43
5	Same as (4) except 0.018 inch diameter holes were punched	525	571 ± 54
6	Same as (1) except 0.025 inch holes were drilled	579	594 ± 57
7	Same as (1) except .031 inch holes were drilled	551	589 ± 54
8	Same as (7) only central 40% of specimens were perforated	611	593 ± 40
9**	Same as (1) except longitudinal spacing decreased to 0.05 inches	626	603 ± 40
10	0.070 inch mahogany-mahogany plywood 0.018 inch diameter holes spaced 0.05 inch apart in transverse rows, longitudinal spacing of rows- 0.10 inches. Face grain direction parallel to loading direction-entire cross section perforated	316	326 ± 25
11**	Same as (10) except transverse spacing of 0.1 inch and longitudinal spacing of 0.05 inch	386	331 ± 27

*Based on 100% efficiency being 6700 #/in^2 for the 1/8 inch mahogany - yellow poplar plywood and 7200 #/in^2 for the 0.070 inch mahogany - mahogany plywood. These are the mean strengths of 10 standard A.S.T.M. plywood tension specimens.

**Presented as an illustration of the fact that such holes spaced closer than 0.1 inch in the direction of loading reduce the efficiency of the material.

TABLE 11

The Effect of a Single Hole Placed in the Center of the Test Area of a Specimen On Its Ultimate Shear Strength - 1/8 Inch Mahogany - Yellow Poplar Plywood - Face Grain Perpendicular to Loading

Test No*	Percent Area Removed by Single Hole	Percent Original** Shear Based on Net Area
1	4	101 ± 5
2	5	105 ± 4.5
3	6.5	102 ± 5.5
4	10.4	99 ± 5
5	14.8	97.5 ± 4.5
6	20	103 ± 4
7	25	99 ± 4.5
8	31.6	98 ± 6
9	35	98 ± 6
10	40	102 ± 6
11	45.5	104 ± 5
12	50	96 ± 4.5

*Each test represents the mean of 10 test values.

**Based on mean of 10 tests to determine the ultimate shear strength of the unperforated material - mean value 1640 #/in^2 as compared with guaranteed minimum of 1440 #/in^2 as given in the ANC-18.

TABLE 12

Ultimate Shear Strength Perforated
1/8 Inch Mahogany - Yellow Poplar Plywood

Test** No.	Drill* Diam.	Trans.* Spac.	Long.* Spac.	No of Rows	No of Holes in Row	Exp. Ult. Failure	% Orig.*** Strength	Pred. Ult. Stress
			(Loading perpendicular to grain)[1]					
1	.018	.1	.1	3	2	198	104	190
2	.025	.1	.1	3	2	177	96.5	185
3	.031	.1	.1	3	2	176	98.5	179
4	.018	.1	.1	3	3	187	102	183
5	.025	.1	.1	3	3	171	98	174
6	.031	.1	.1	3	3	161	96.5	167
			(Loading parallel to grain)[2]					
7	.018	.1	.1	3	2	203	104.5	194
8	.025	.1	.1	3	2	183	97.5	188
9	.031	.1	.1	3	2	192	105	183
10	.018	.1	.1	3	3	190	101.5	187
11	.025	.1	.1	3	3	189	107	177
12	.031	.1	.1	3	3	173	101.5	170

*All dimensions in inches.

**Each test represents mean of 10 test values.

***Percent original strength based on net area.

1. Probable ultimate strength failure - 1640 #/in^2 (Based on 10 tests).
2. Probable ultimate strength failure - 1670 #/in^2 (Based on 10 tests).

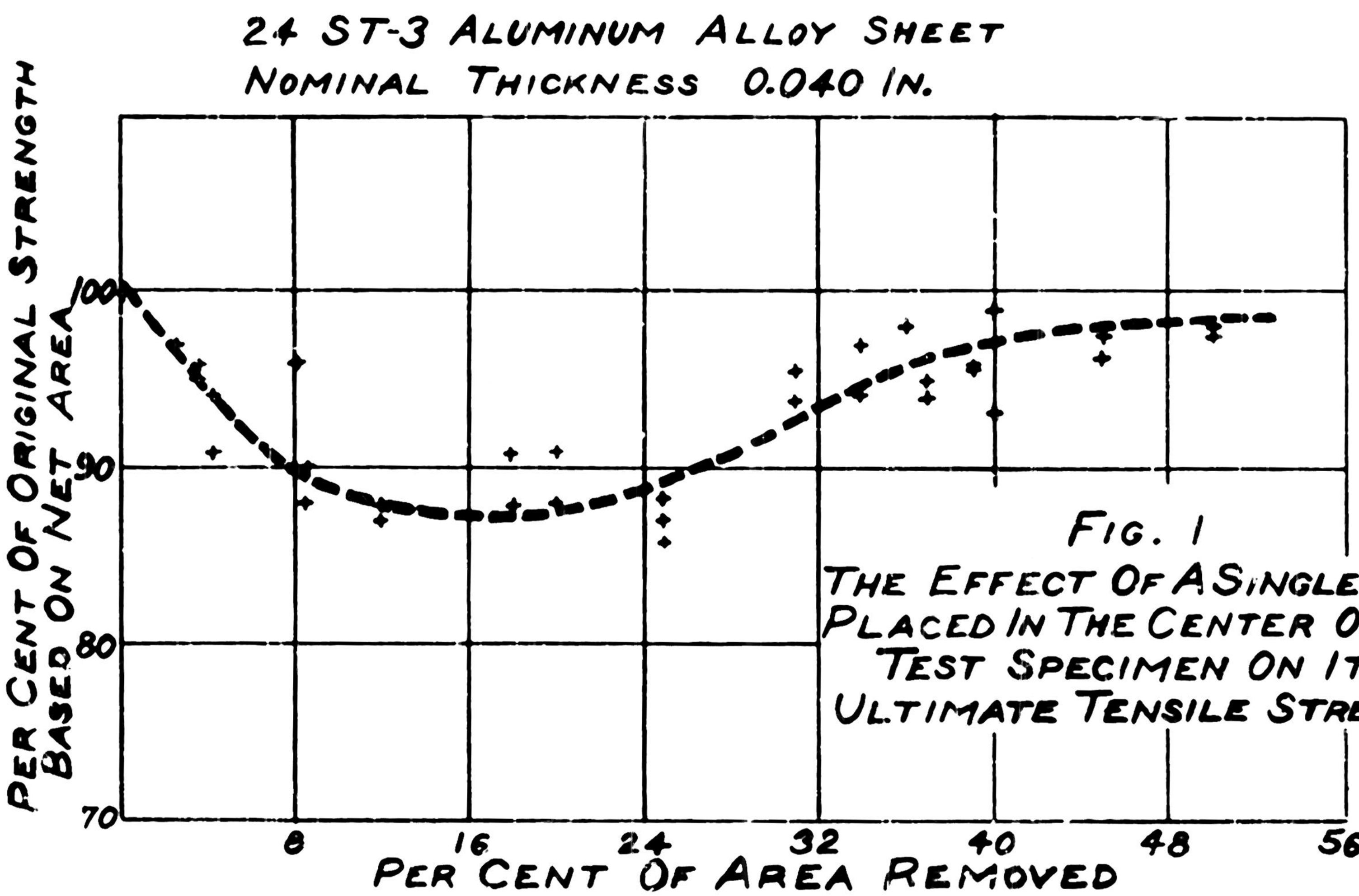

Fig. 1
The Effect Of A Single Hole Placed In The Center Of The Test Specimen On Its Ultimate Tensile Strength

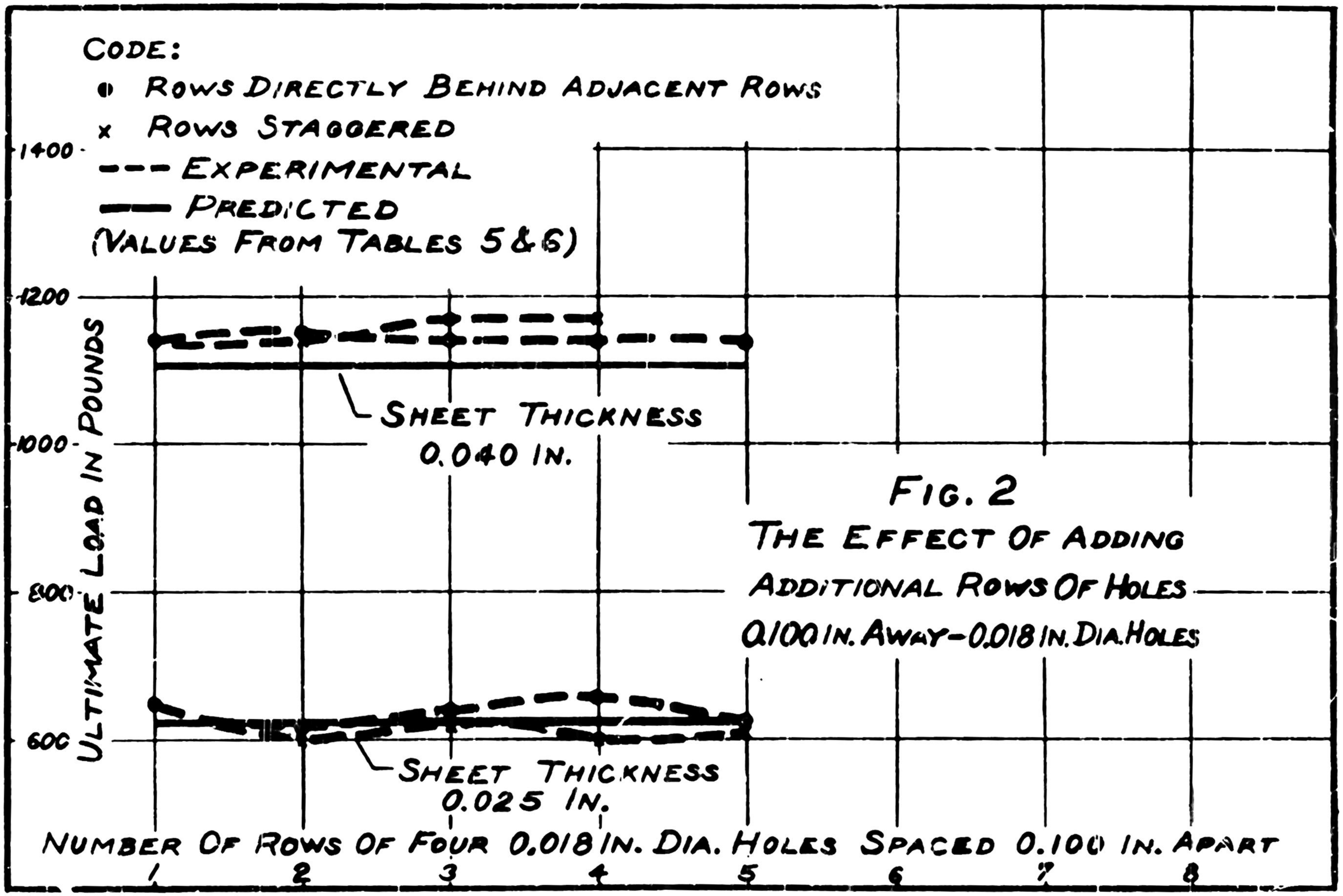

FIG. 2
THE EFFECT OF ADDING
ADDITIONAL ROWS OF HOLES
0.100 IN. AWAY-0.018 IN. DIA. HOLES

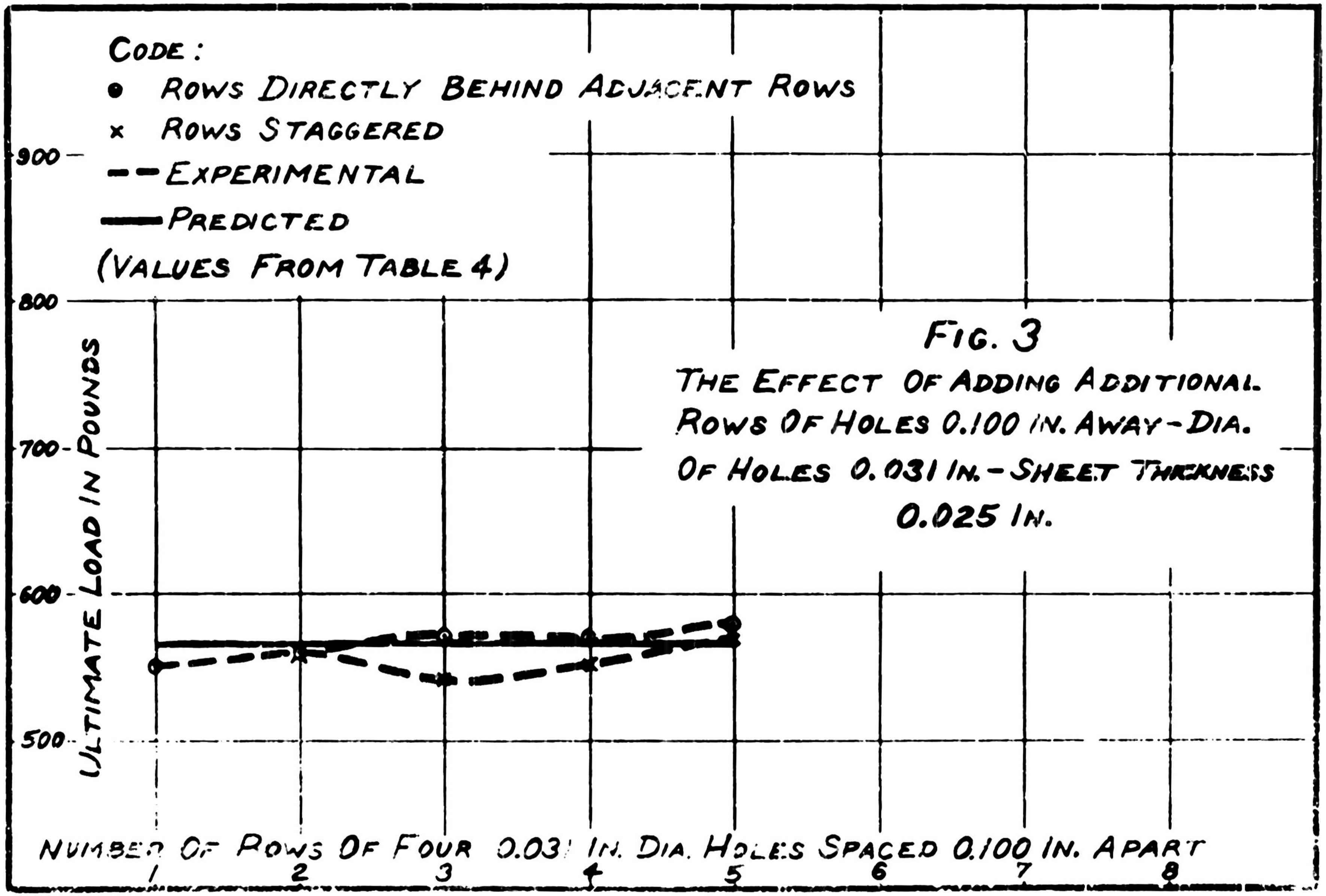

FIG. 3

THE EFFECT OF ADDING ADDITIONAL ROWS OF HOLES 0.100 IN. AWAY - DIA. OF HOLES 0.031 IN. - SHEET THICKNESS 0.025 IN.

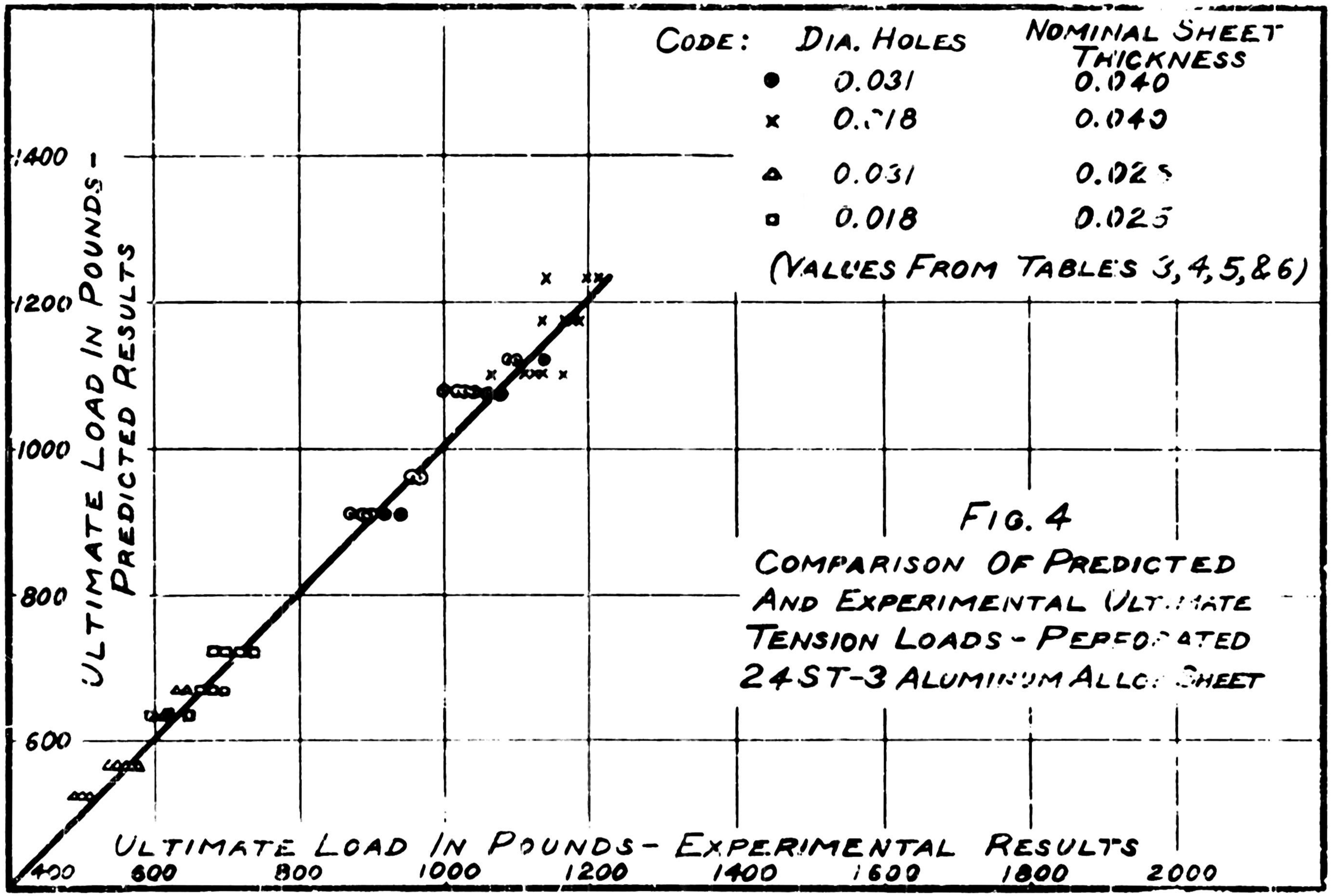

FIG. 4

COMPARISON OF PREDICTED AND EXPERIMENTAL ULTIMATE TENSION LOADS - PERFORATED 24ST-3 ALUMINUM ALLOY SHEET

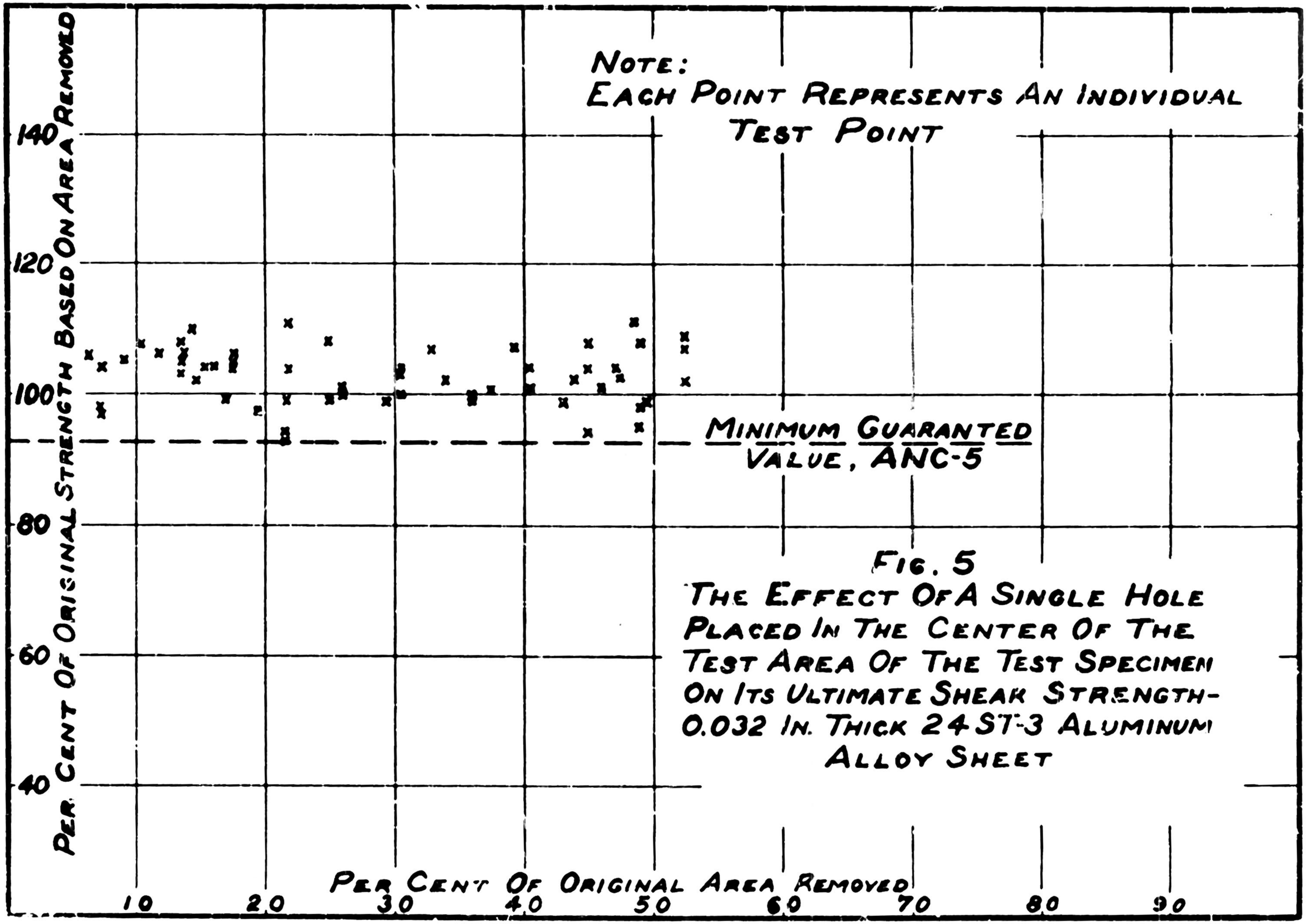

Fig. 5
The Effect Of A Single Hole Placed In The Center Of The Test Area Of The Test Specimen On Its Ultimate Shear Strength - 0.032 In. Thick 24ST-3 Aluminum Alloy Sheet

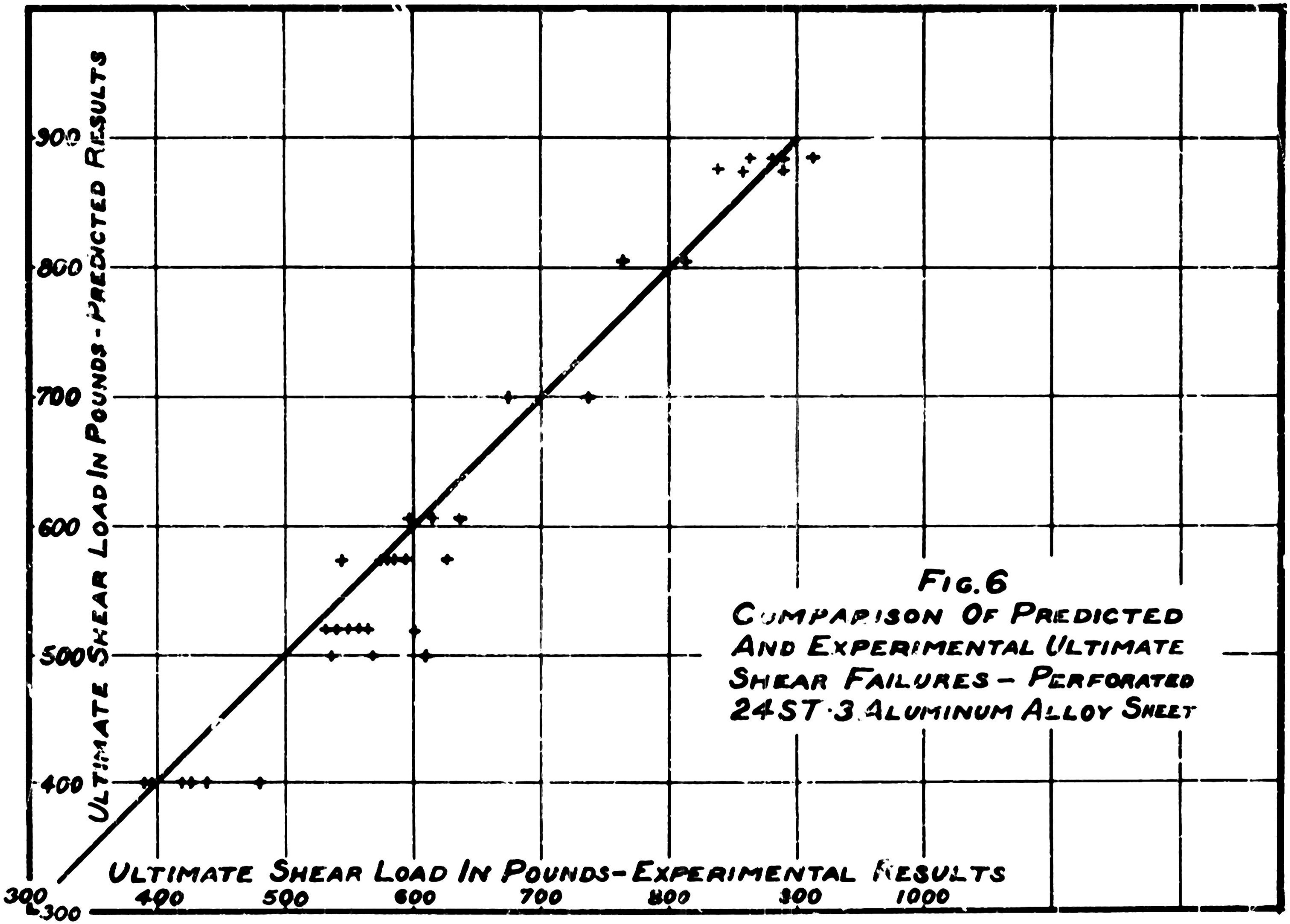

Fig. 6
Comparison Of Predicted And Experimental Ultimate Shear Failures – Perforated 24ST-3 Aluminum Alloy Sheet

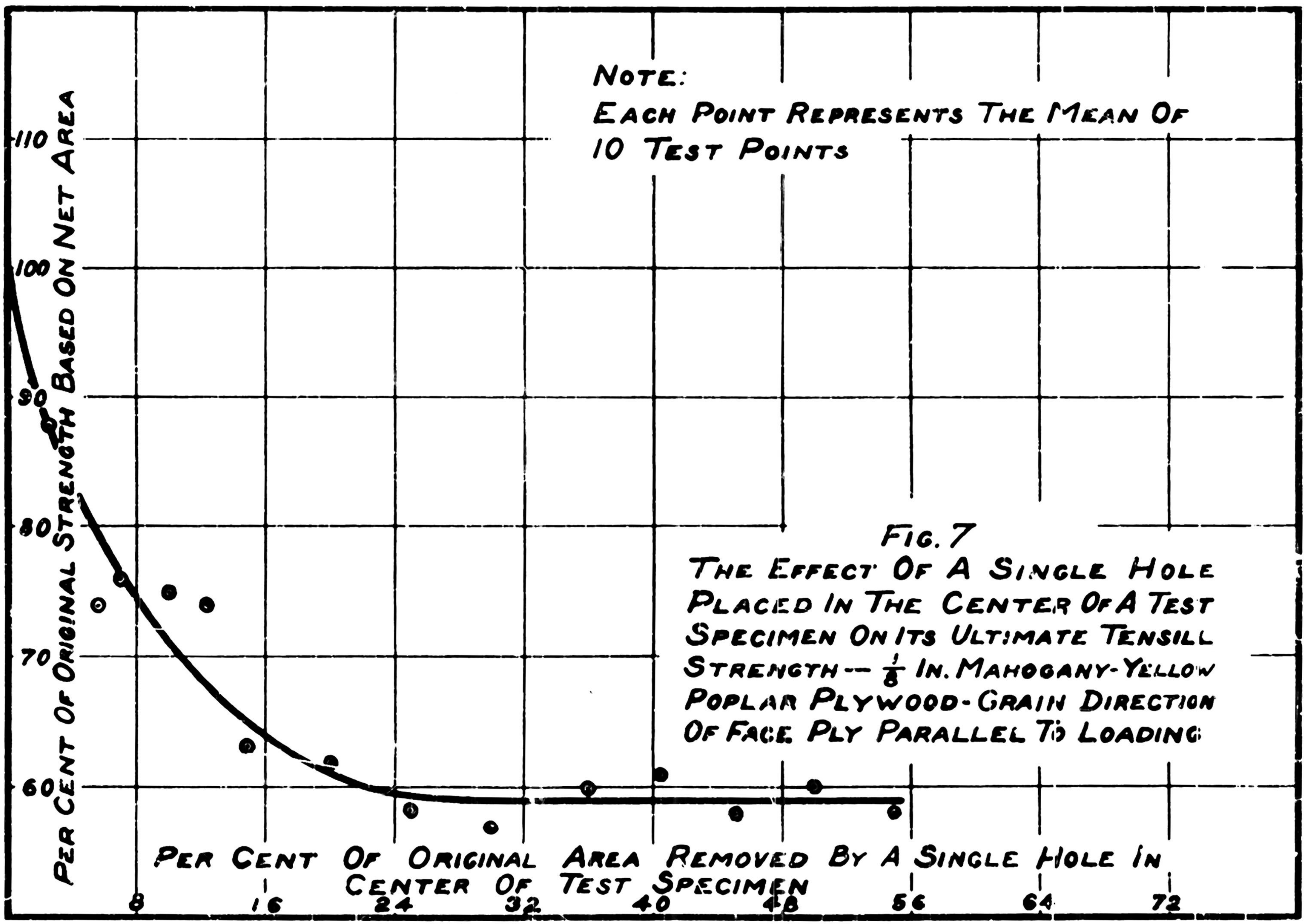

Fig. 7
The Effect Of A Single Hole Placed In The Center Of A Test Specimen On Its Ultimate Tensill Strength -- $\frac{1}{8}$ In. Mahogany-Yellow Poplar Plywood-Grain Direction Of Face Ply Parallel To Loading

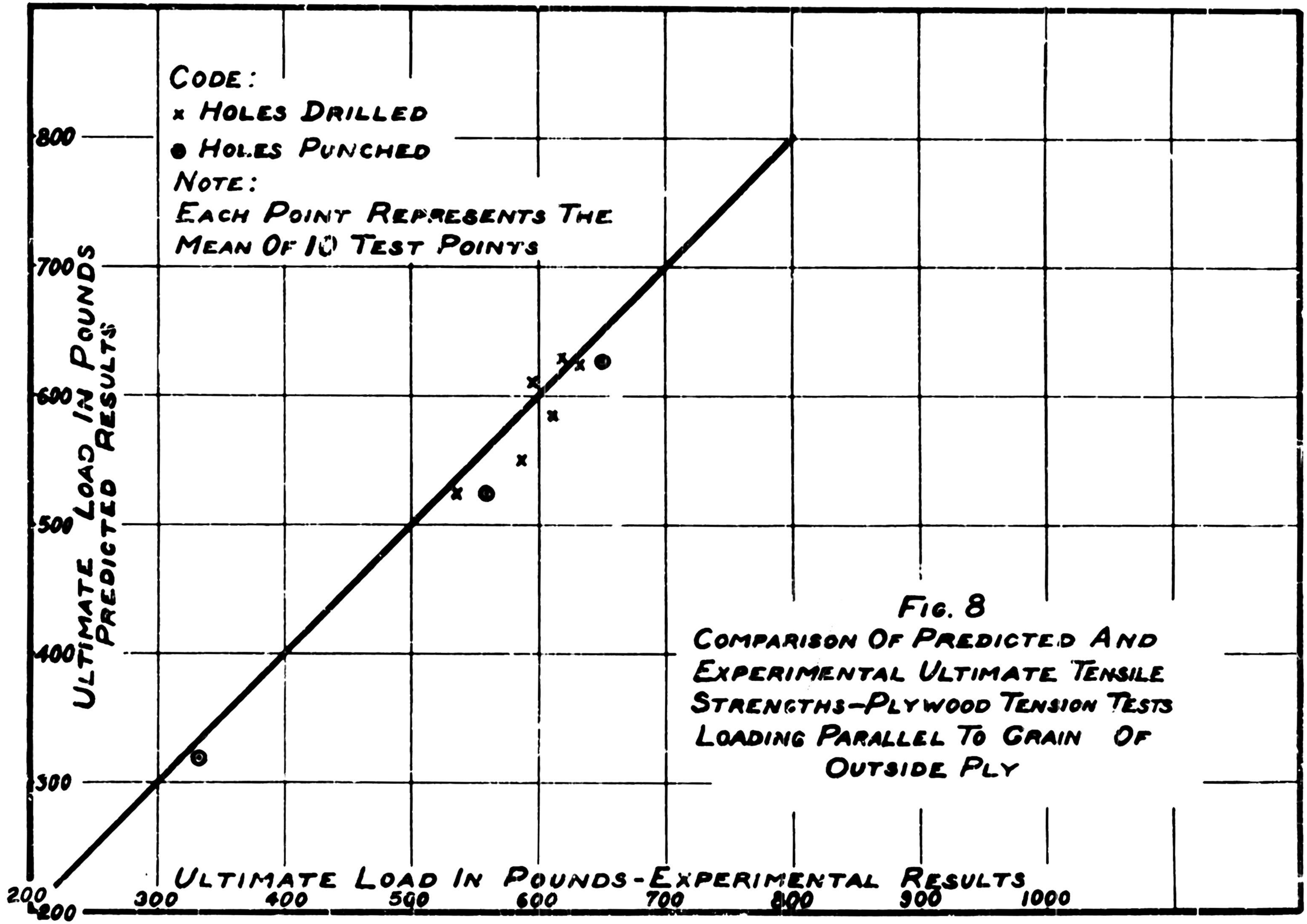

Fig. 8
Comparison Of Predicted And Experimental Ultimate Tensile Strengths—Plywood Tension Tests Loading Parallel To Grain Of Outside Ply

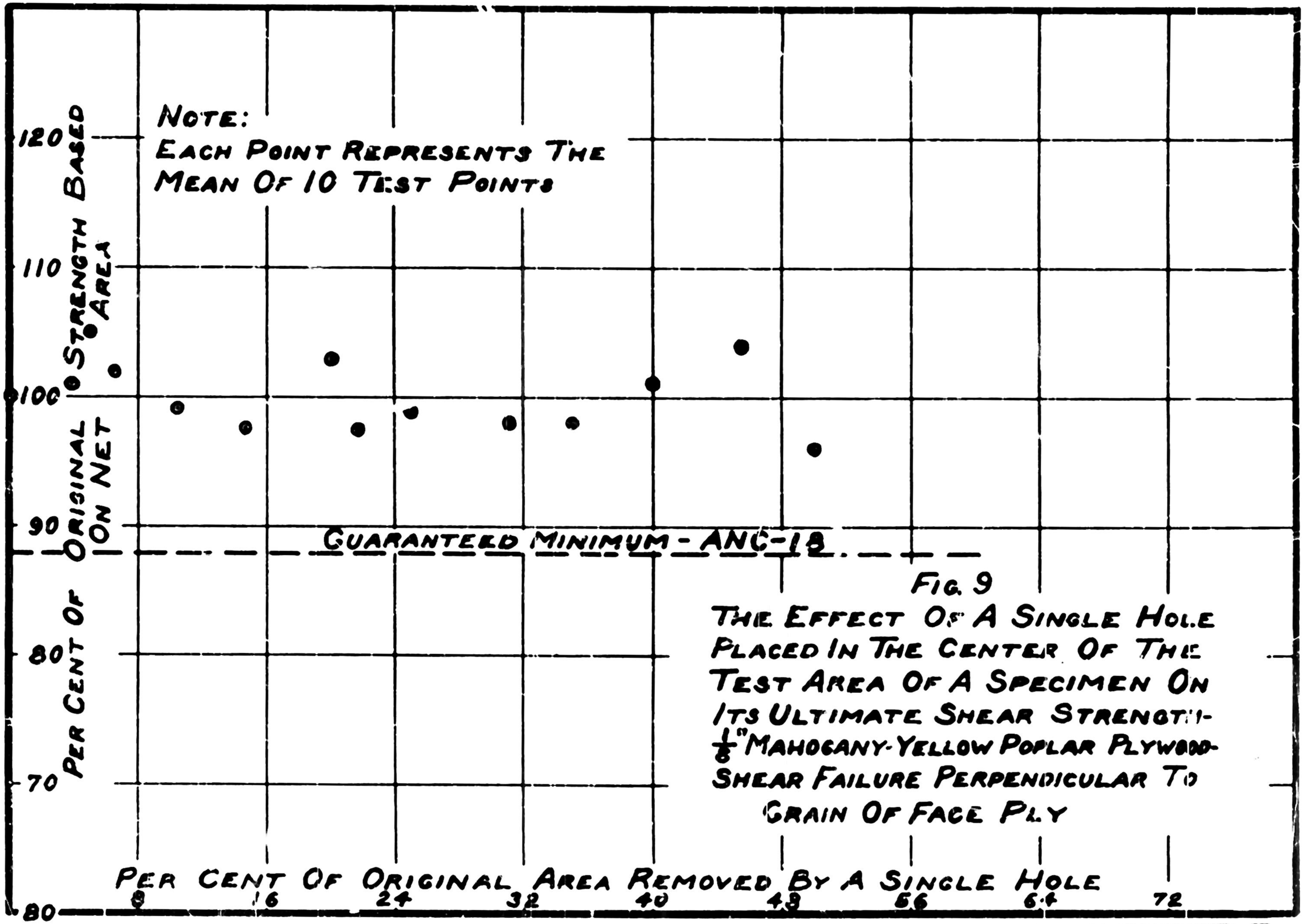

FIG. 9
THE EFFECT OF A SINGLE HOLE PLACED IN THE CENTER OF THE TEST AREA OF A SPECIMEN ON ITS ULTIMATE SHEAR STRENGTH-
$\frac{1}{8}$" MAHOGANY-YELLOW POPLAR PLYWOOD-
SHEAR FAILURE PERPENDICULAR TO GRAIN OF FACE PLY

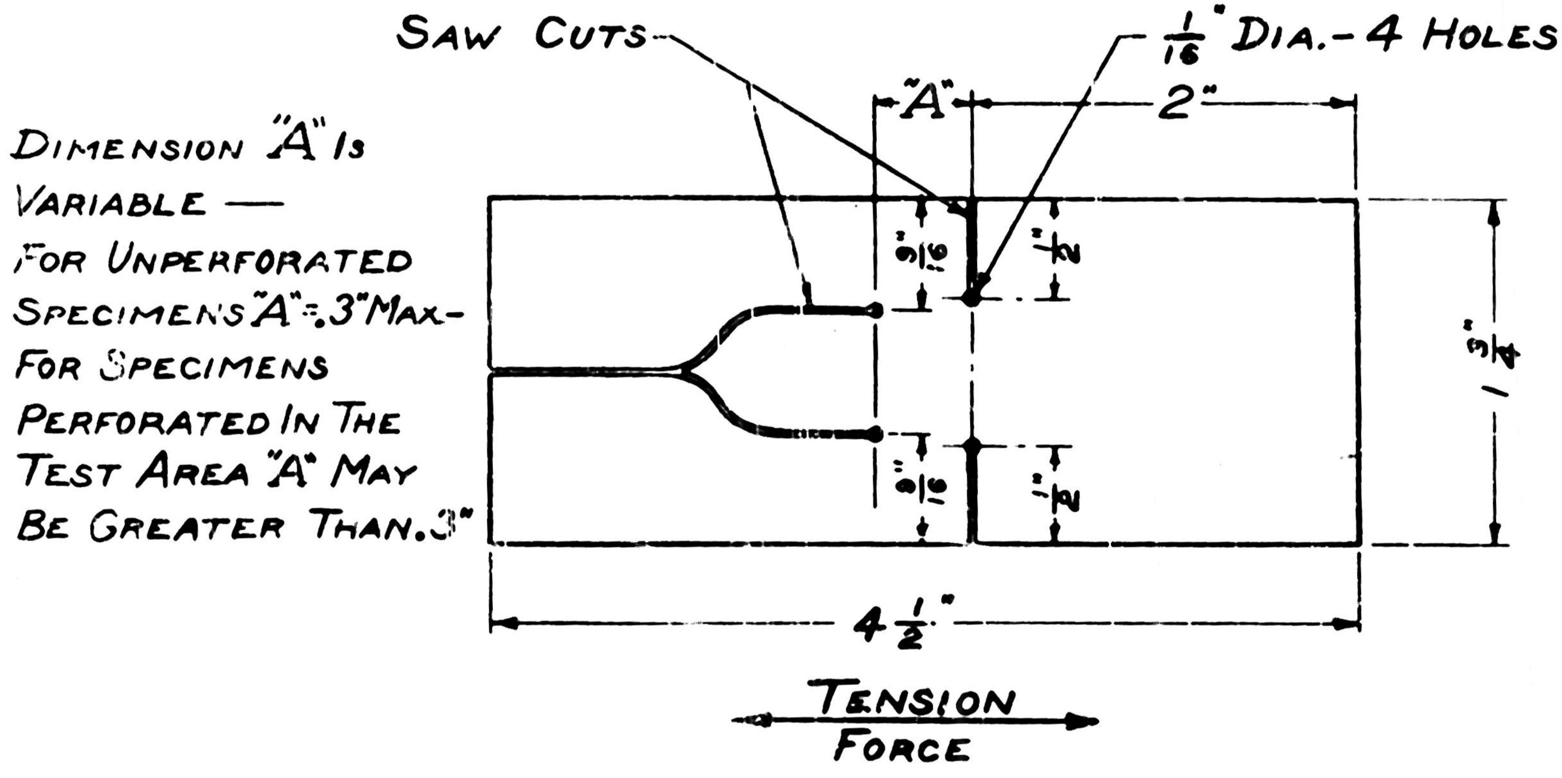

FIG. 10

SHEET ALUMINUM TENSION TYPE SHEAR SPECIMEN